



## **Synthetic Aperture Radar for wind energy applications: potential and challenges at high wind speeds**

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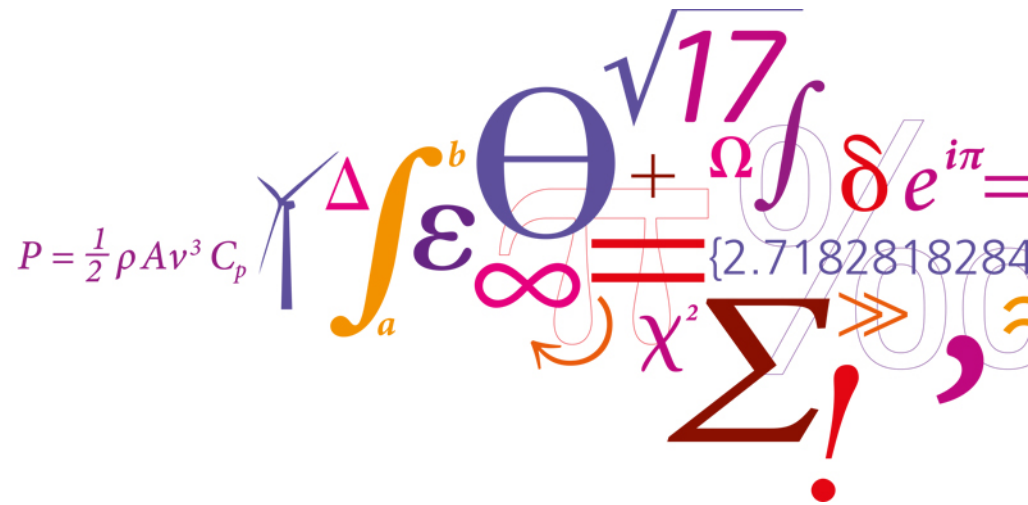
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# Synthetic Aperture Radar for wind energy applications: potential and challenges at high wind speeds

**Merete Badger**

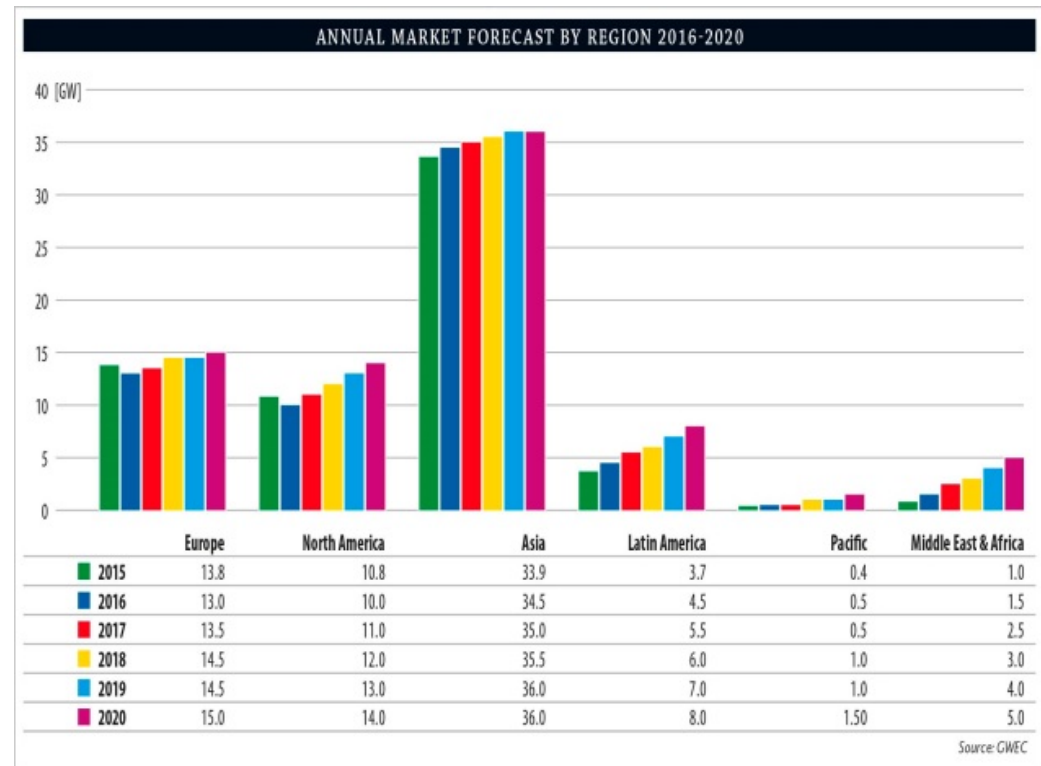
Xiaoli Guo Larsén  
Charlotte Hasager  
Tobias Ahsbahs  
Andrea Hahmann  
Alfredo Peña  
Jake Badger



# Offshore wind energy



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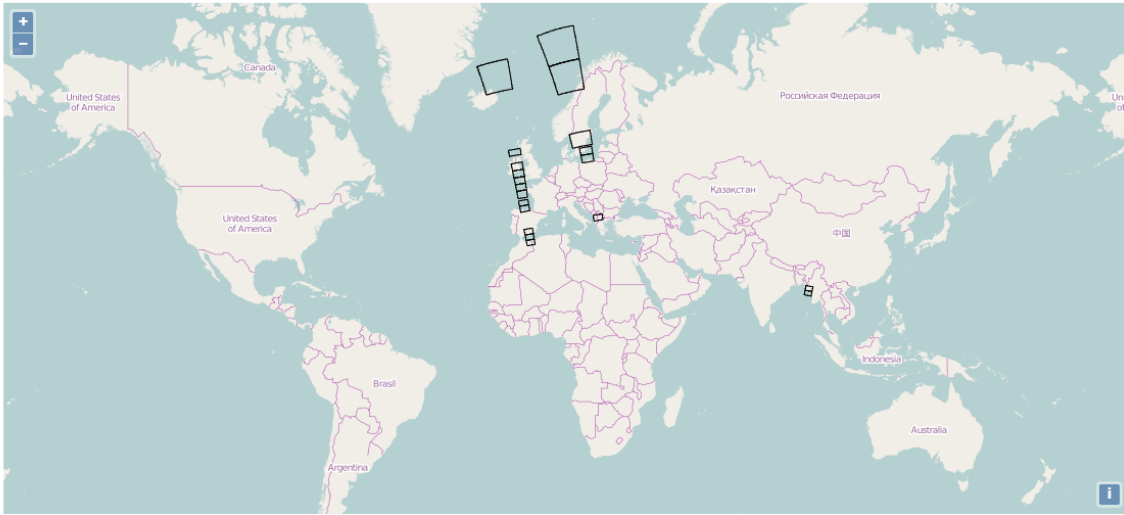
*Annual wind power installations 2016-2020.  
 Source: GWEC.*

# SAR wind data archive at DTU

- 30,000+ ENVISAT ASAR scenes (2002-2011)
- 36,000+ Sentinel-1 A/B SAR scenes (2014->)

DATA STATION

Home Satellite winds



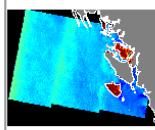
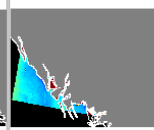
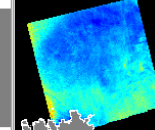
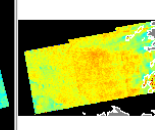


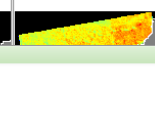

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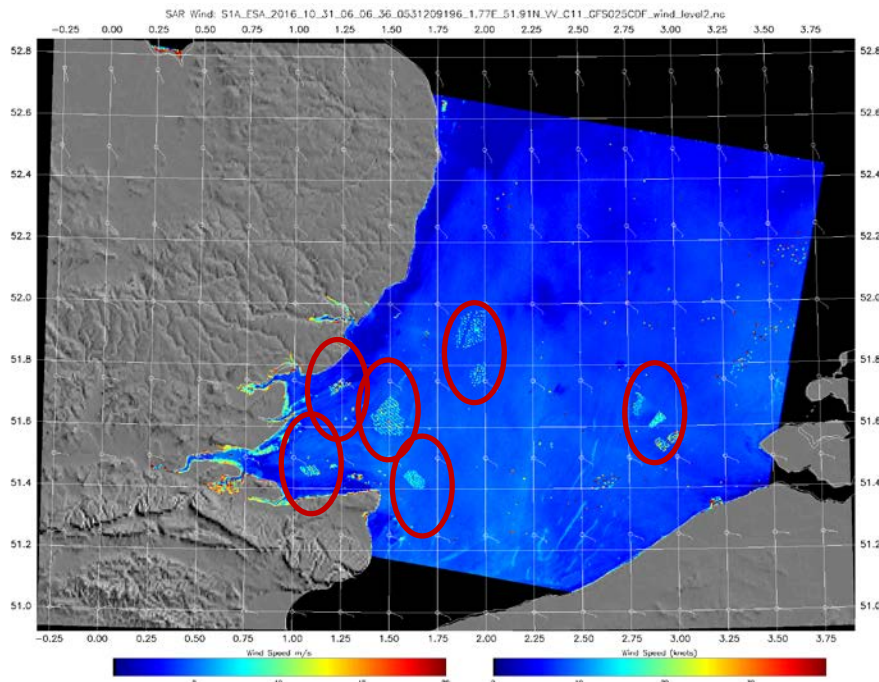
# SAR Ocean Products System (SAROPS)

- Evolved from the APL/NOAA SAR Wind Retrieval System  
<http://fermi.jhuapl.edu/>
- SAR wind retrieval in near-real-time
- NOAA covers polar seas and US coastlines (operational)

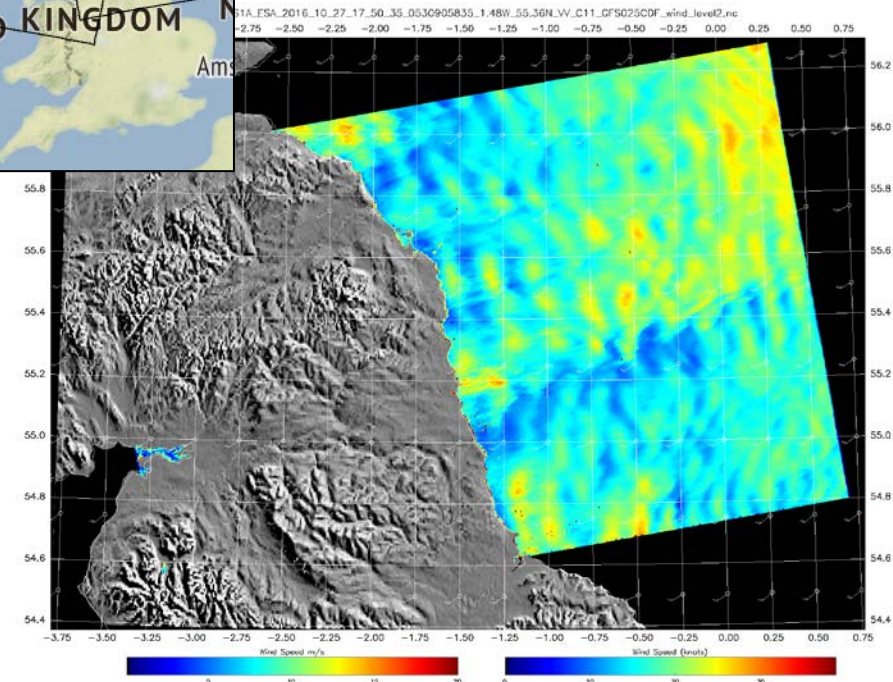
Monaldo, F.M *et al.* (2015): A Weather Eye on Coastal Winds, *Eos*, 96,  
doi: 10.1029/2015EO034581)

- DTU covers the European seas (routine)

# Sentinel-1 A retrievals over the UK



October 31, 2016 at 06:06 UTC

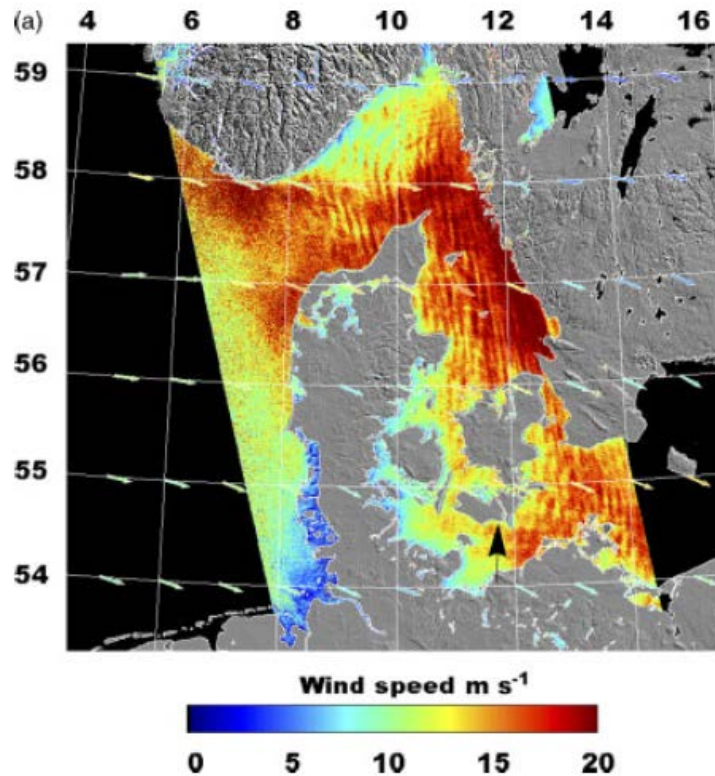


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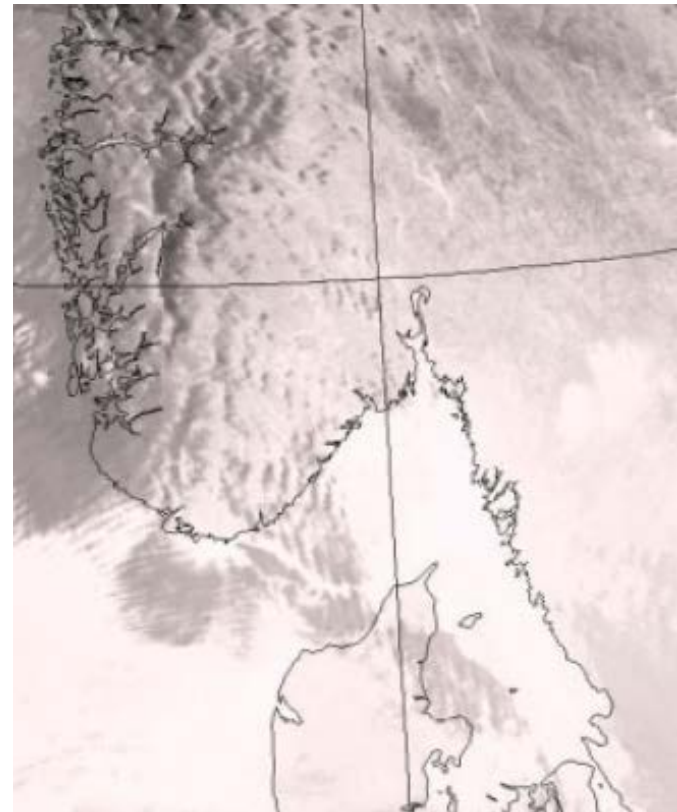


# Mountain gravity waves

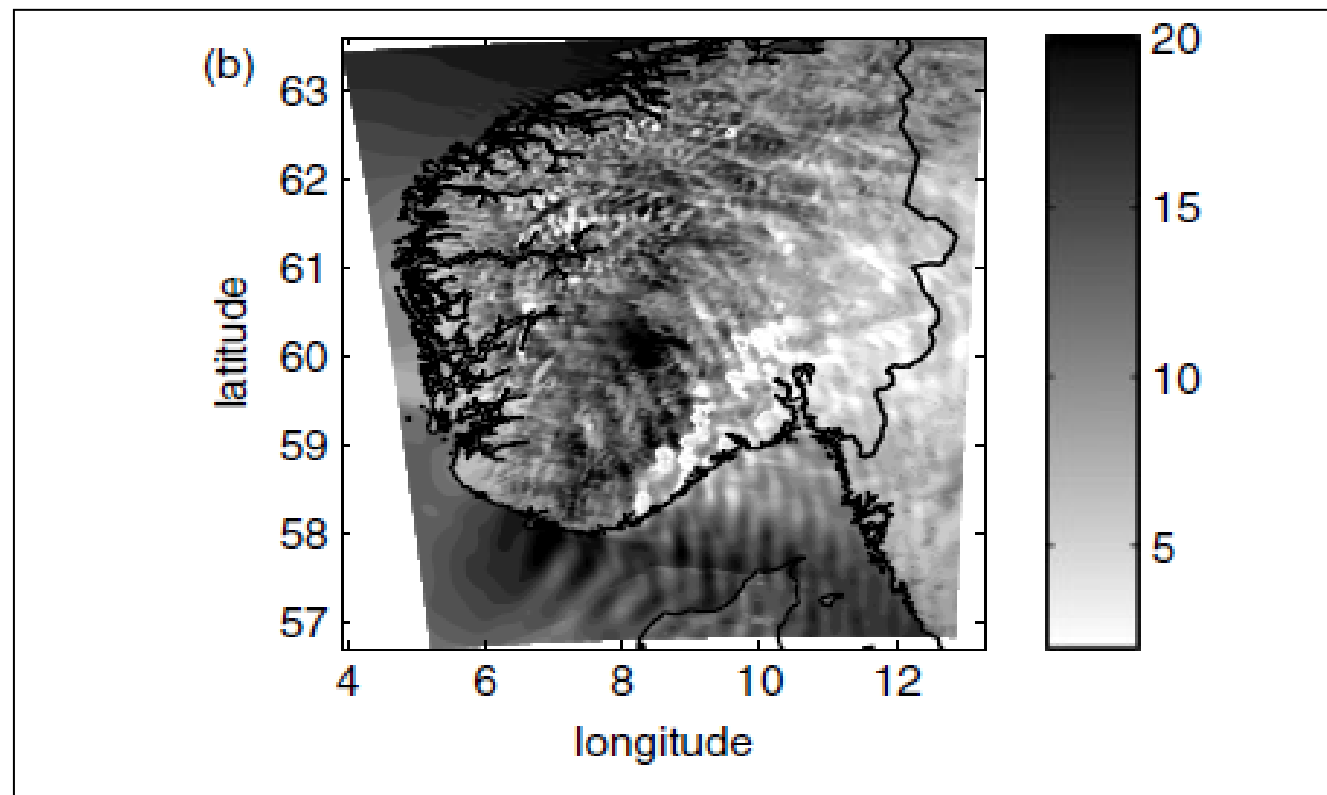
November 6, 2006



*Envisat ASAR 10-m wind speed*



*Cloud image*



*WRF wind speed*

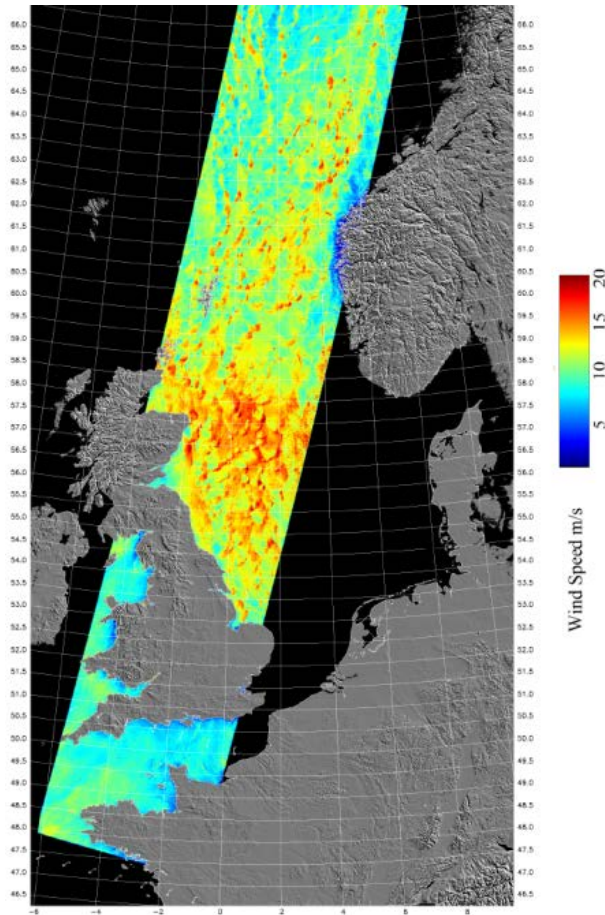
Larsén X., Larsen S. and Hahmann N. A. 2012: Origin of the waves in “A case study of mesoscale spectra of wind and temperature, observed and simulated”: Lee waves of the Norwegian mountains, *Q. J. R. Meteorol. Soc.* **137** DOI:10.1002/qj.916, 138: 274-279.

Larsén X., Larsen S. and Badger M. 2011: A case study of mesoscale spectra of wind and temperature, observed and simulated, *Quarterly Journal of Royal Meteorological Society*, Doi: 10.1002/qj.739, 137:264-274.

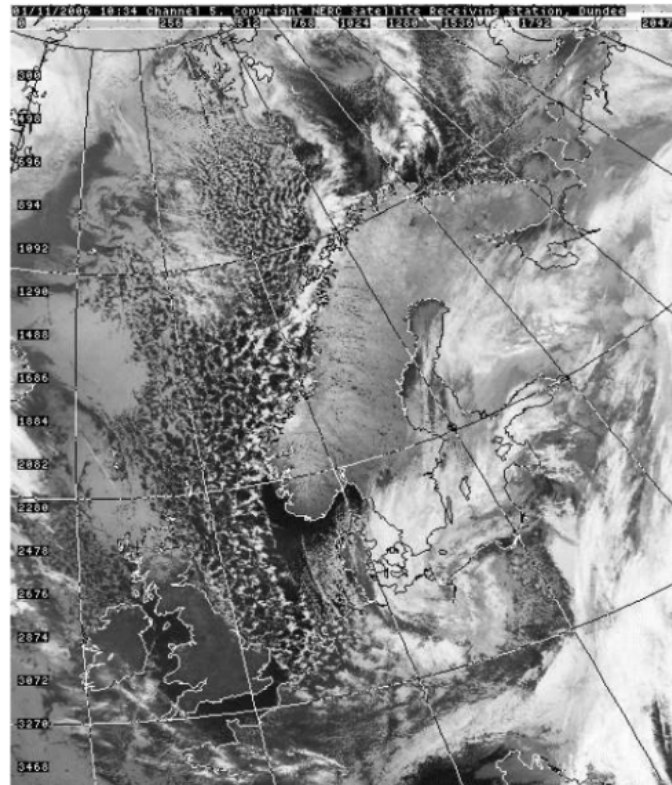
Larsén X., Vincent C. and Larsen S.E. 2013: Spectral structure of mesoscale winds over the water, *Q. J. R. Meteorol. Soc.*, DOI:10.1002/qj.2003, 139, 685-700.



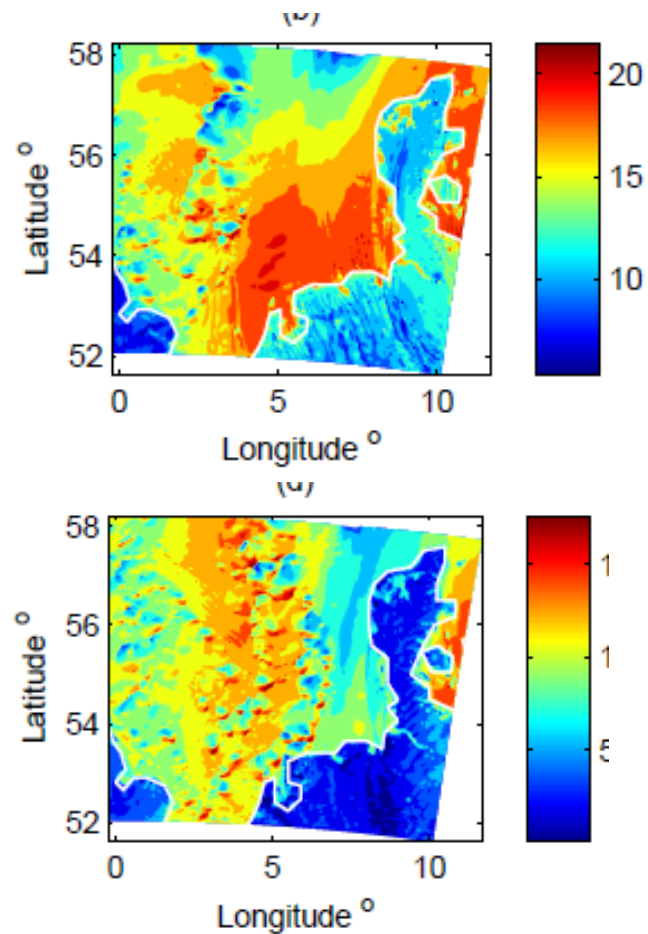
# Open cells



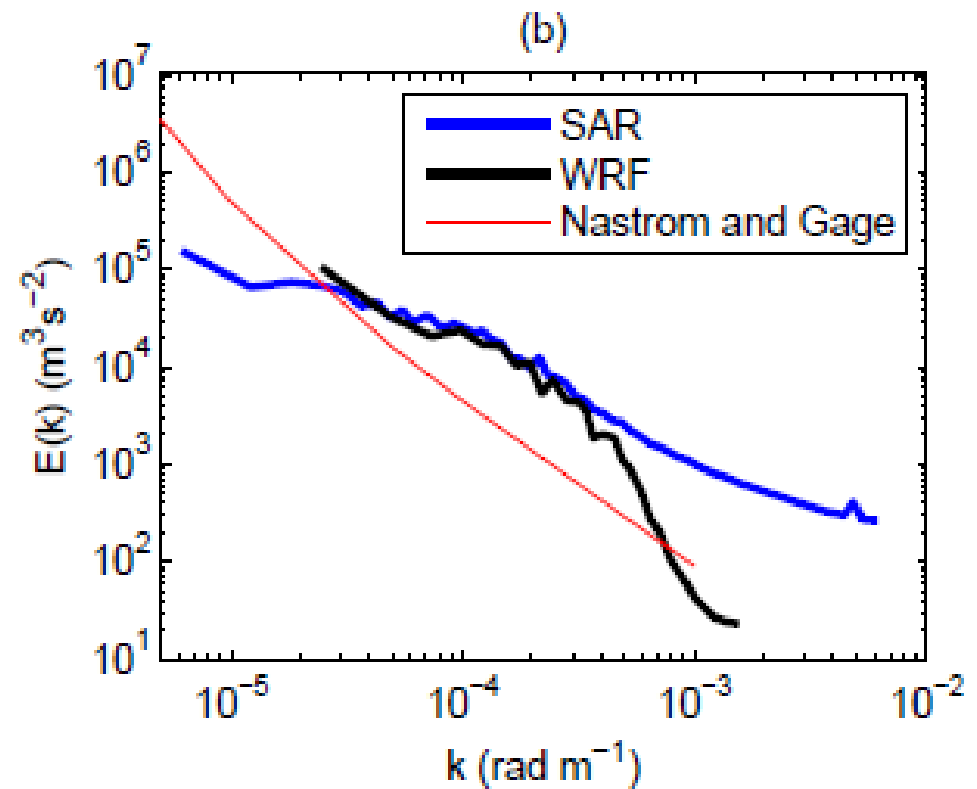
*Envisat ASAR 10-m wind speed*



*Cloud image*



*WRF wind speed*

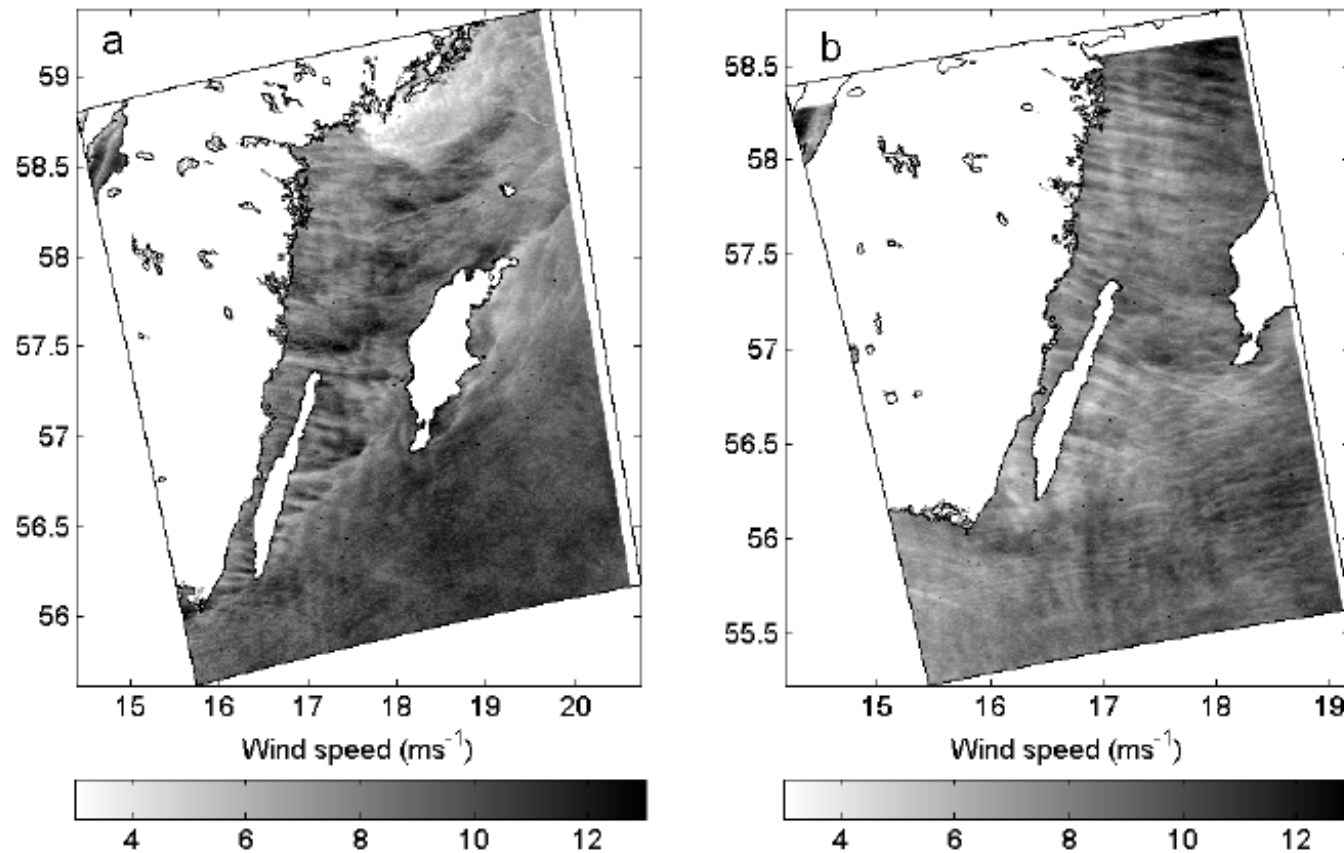


Larsén X., Du J., Bolaños R. and Larsen S. (2016) Storm Britta Revisted, Submitted to Natural Hazards.

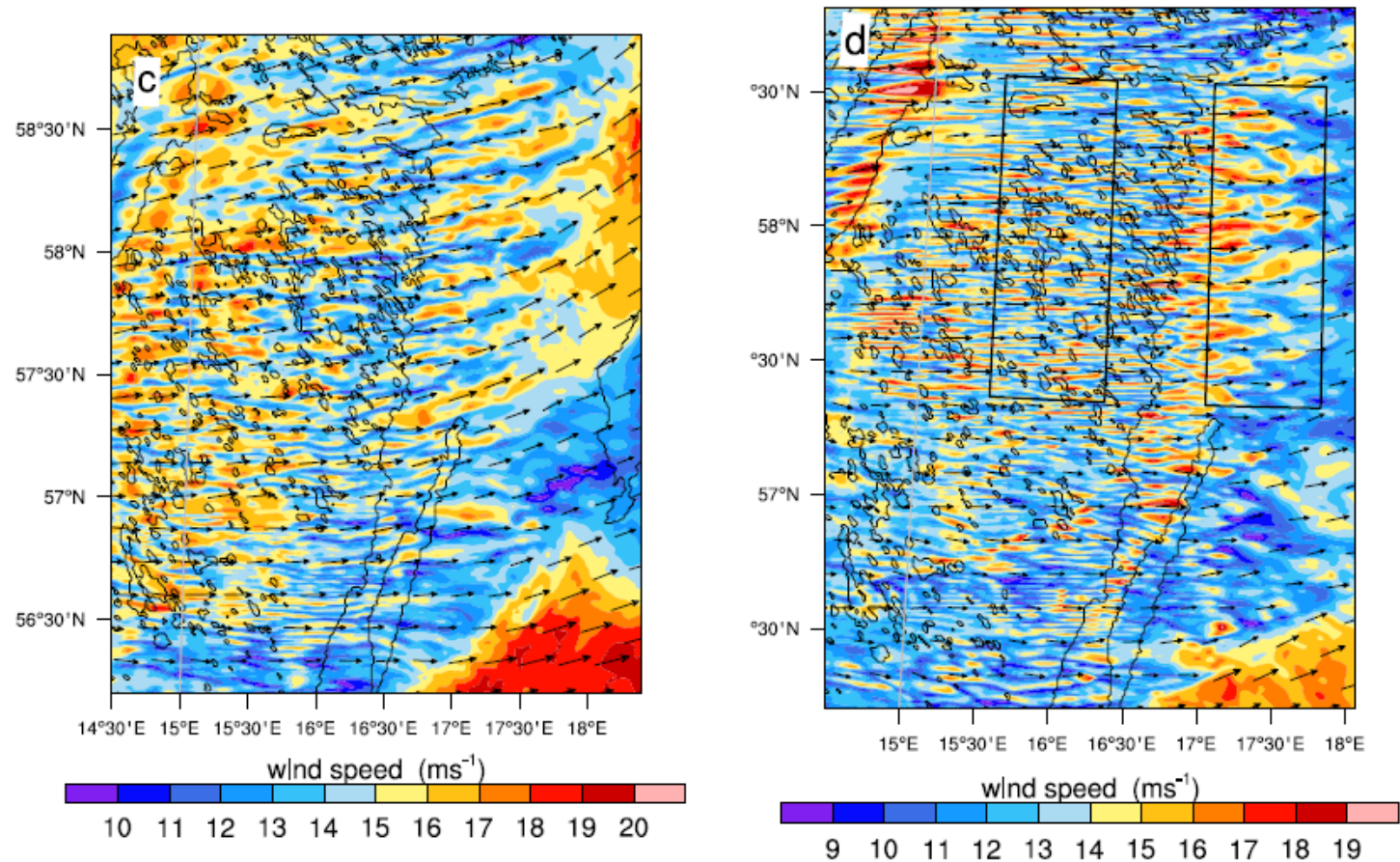
Larsén X., Vincent C. and Larsen S.E. 2013: Spectral structure of mesoscale winds over the water, *Q. J. R. Meteorol. Soc.*, DOI:10.1002/qj.2003, 139, 685-700.

# Boundary layer rolls

May 17 and May 25, 2011



*Envisat ASAR 10-m wind speed*

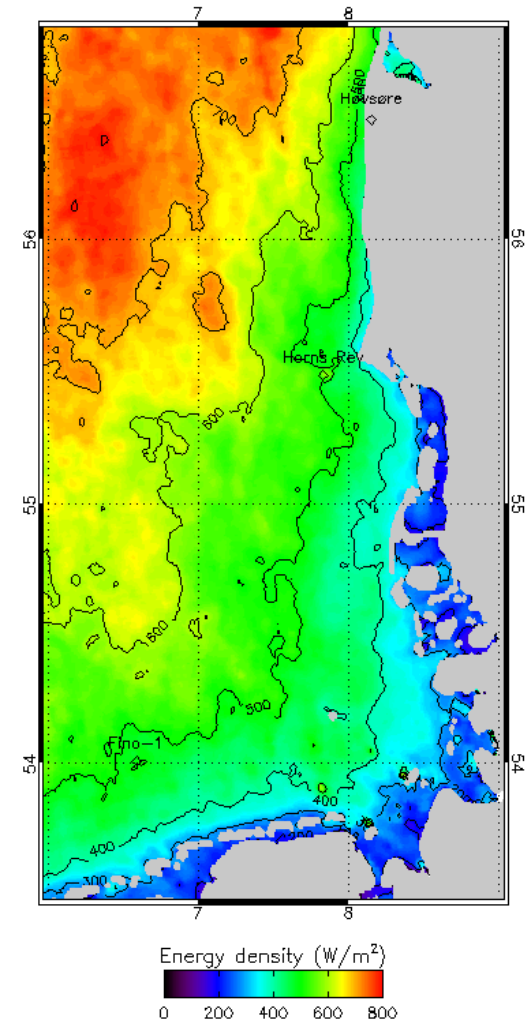
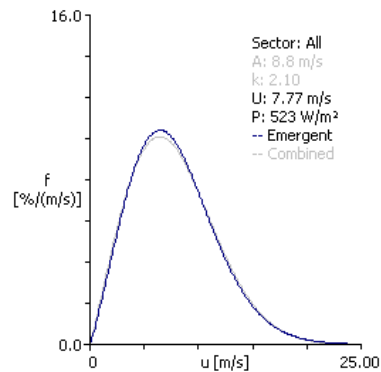
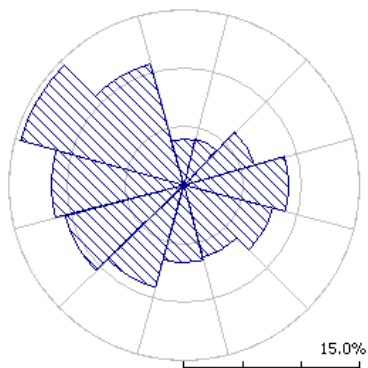
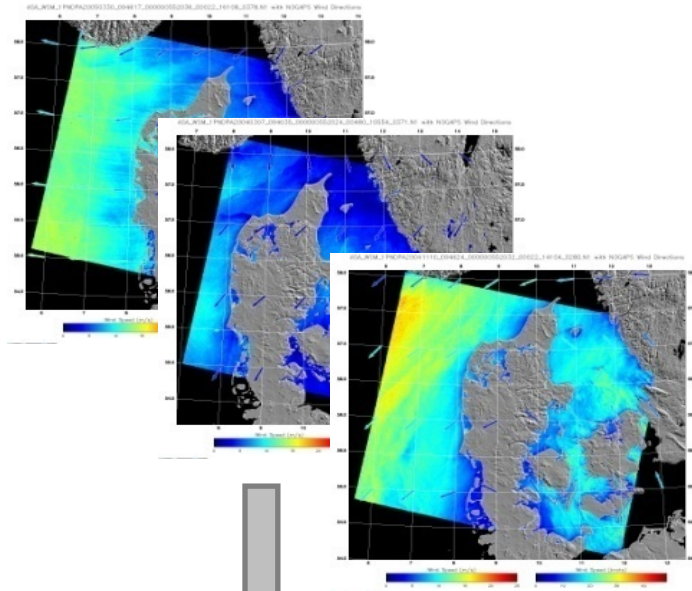


*WRF wind speed*

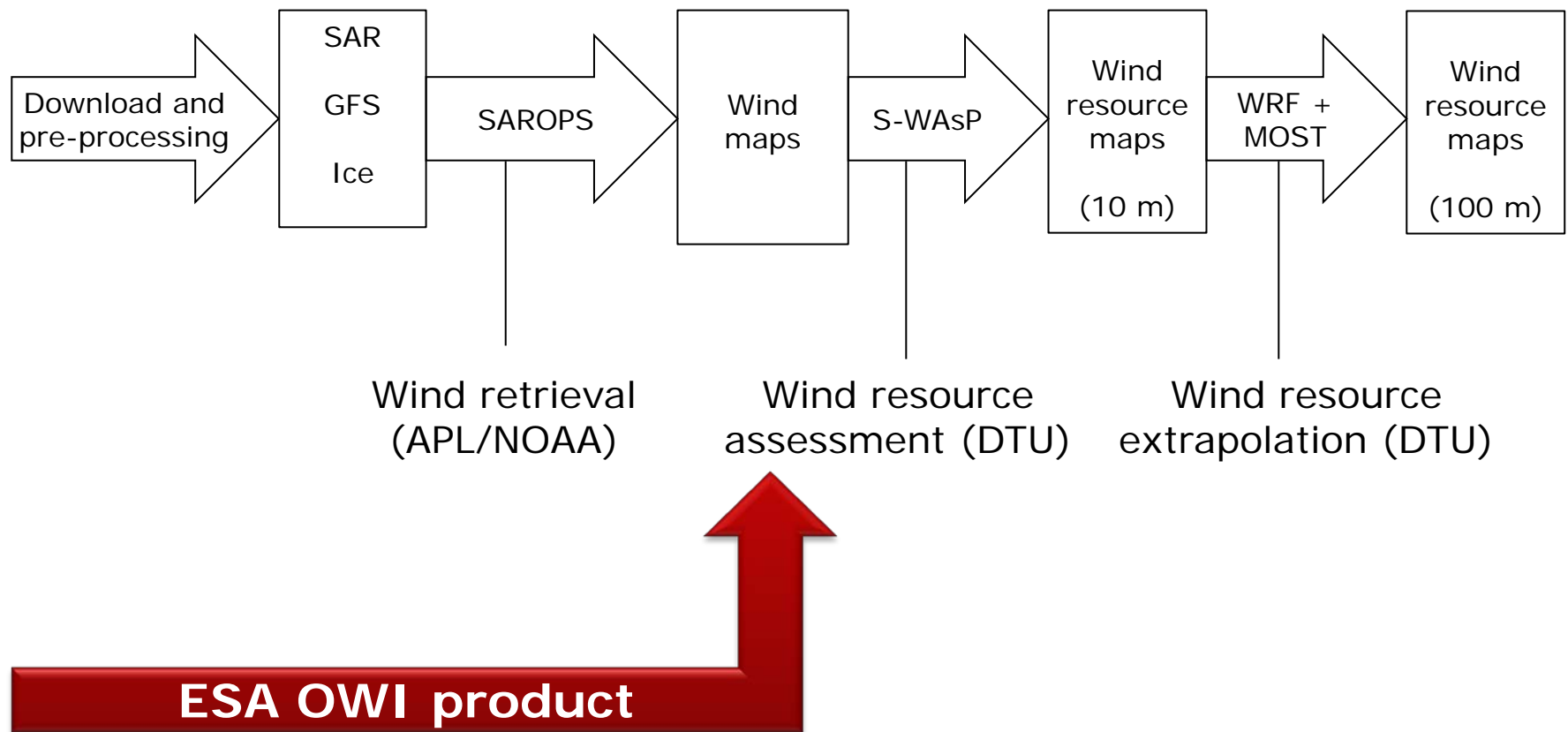
Svensson N., Bergström H., Sahlée E., Nilsson E., Badger M. and Rutgersson A. (2016), Offshore advection of boundary layer rolls, Submitted to BLM.



# Wind resource mapping



# Chain of processes





# The New European Wind Atlas (NEWA)

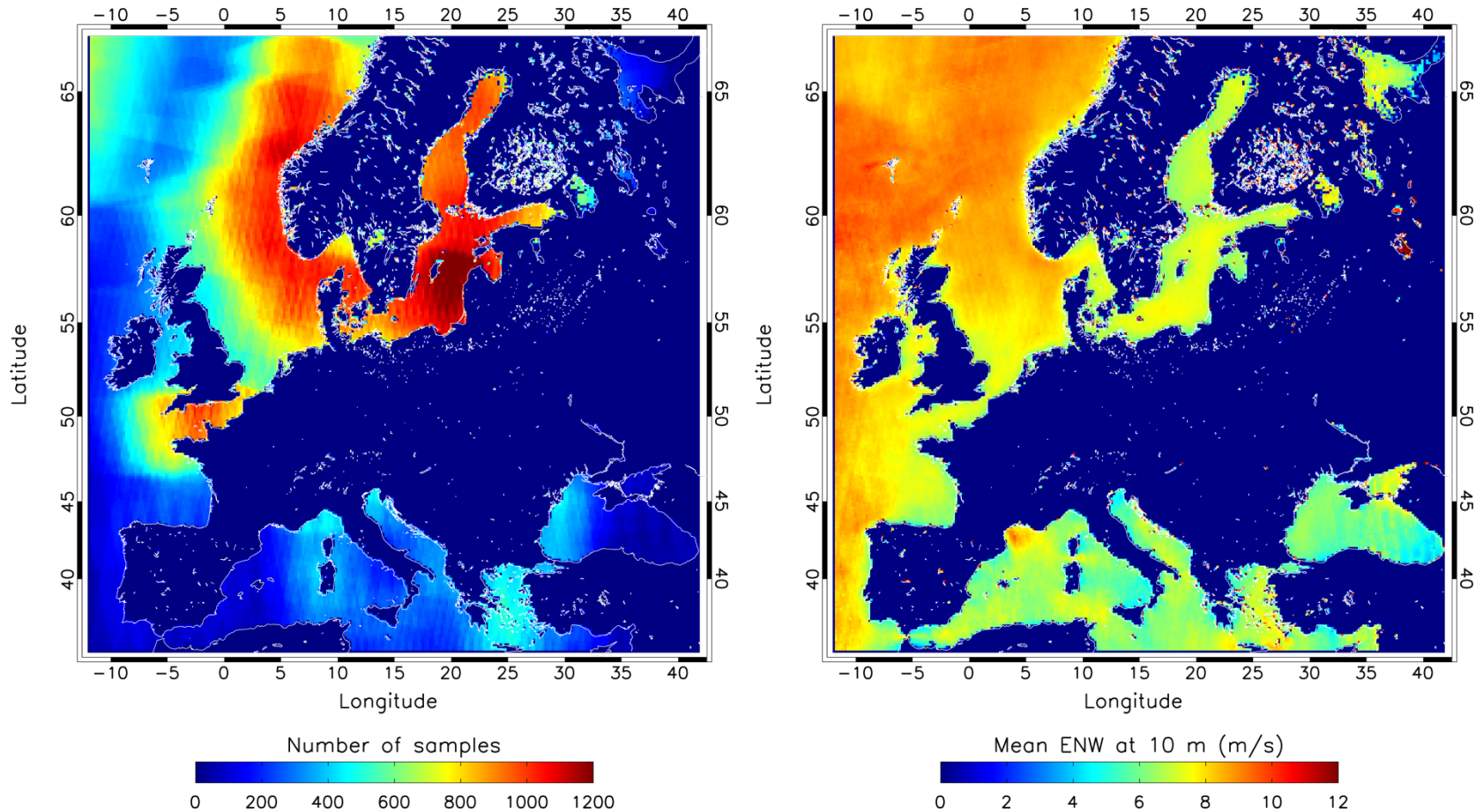
- Envisat ASAR and Sentinel-1 A/B
- Extrapolation to different heights up to 100 m
- Extensive measurement campaigns and modeling



*Coverage of the satellite based atlas in NEWA*

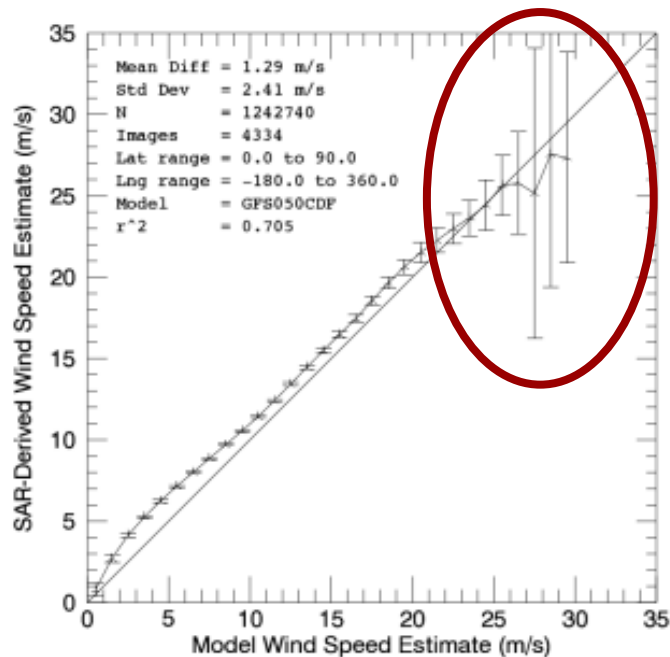
*(image courtesy Google Earth)*

# Preliminary 10-m atlas for Europe

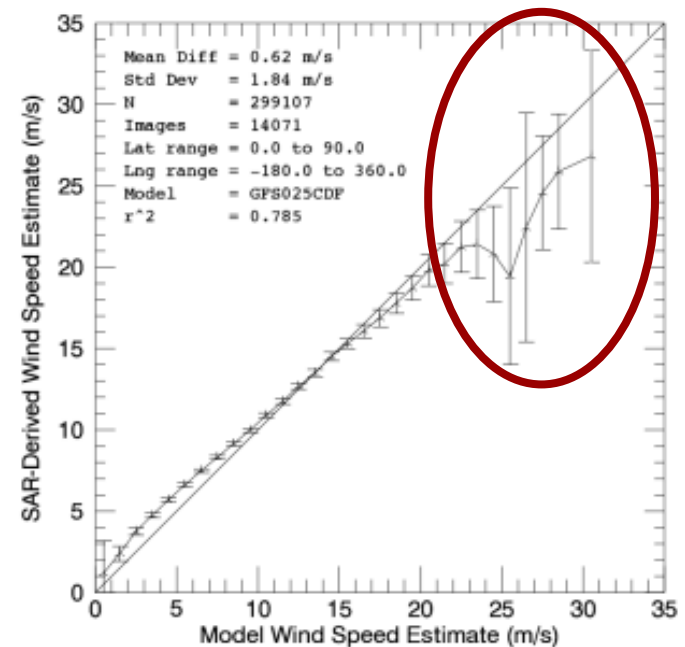


*Envisat ASAR and Sentinel-1A/B combined*

# Wind speed comparisons



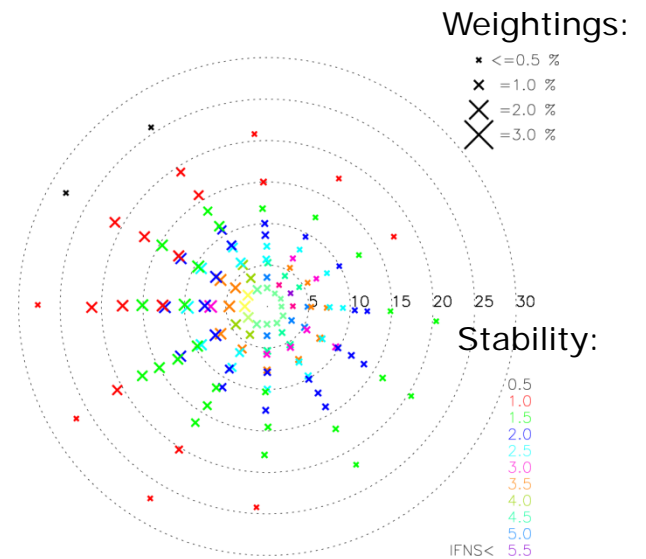
*Envisat ASAR vs. GFS model*



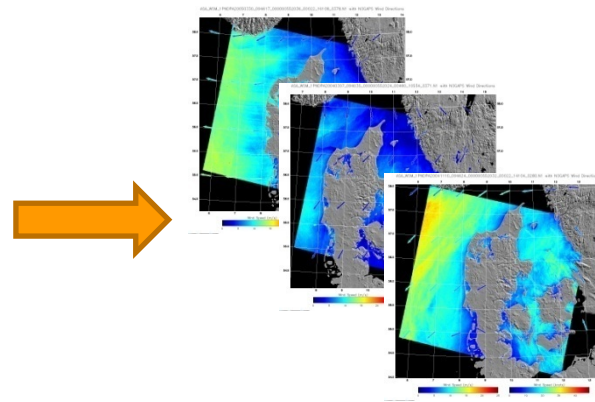
*Sentinel-1A SAR vs. GFS model*

See also: Monaldo, F.M *et al.* (2015): Preliminary evaluation of Sentinel-1A wind speed retrievals. IEEE JSTARS, doi: 10.1109/JSTARS.2015.2504324.

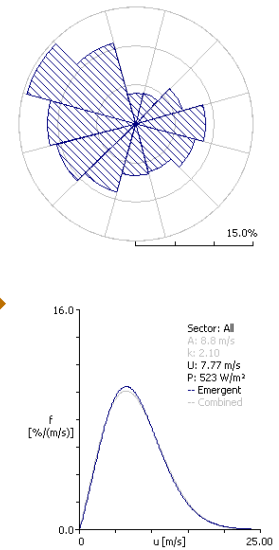
# Wind class sampling



*Wind class definition  
from NCEP/NCAR re-analysis data*



*Population of each wind class  
with a SAR wind field*



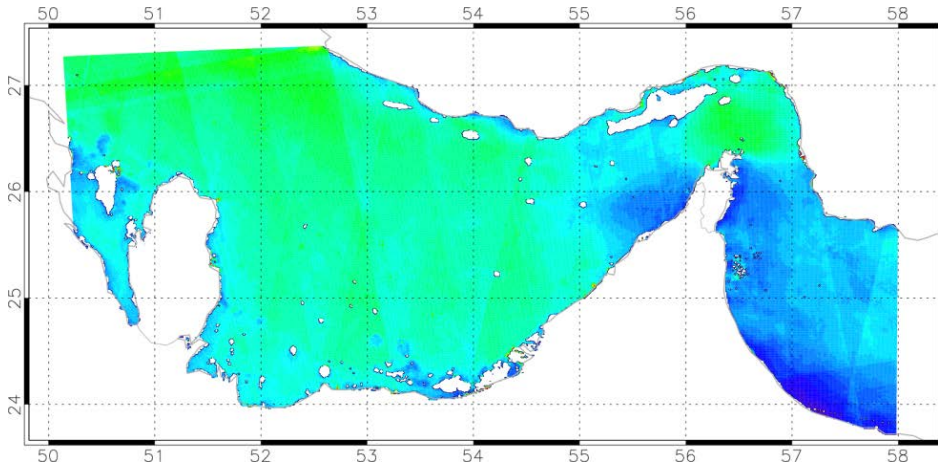
*Weighting and  
Weibull fitting*

Badger et al. (2010): J. Appl. Meteor. Climatol. 49, 2474-2491.

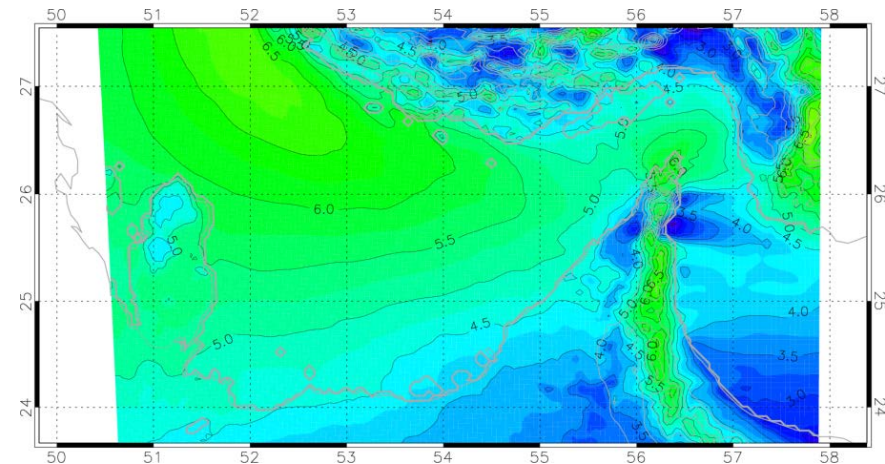
# Advantages of wind class sampling

- Compensates for a limited number of SAR samples
- Long-term wind climatology may be obtained
- Results are directly comparable with mesoscale modeling results

*Example from the UAE:*



*10-m mean wind speed from Envisat  
ASAR data (225 scenes)*

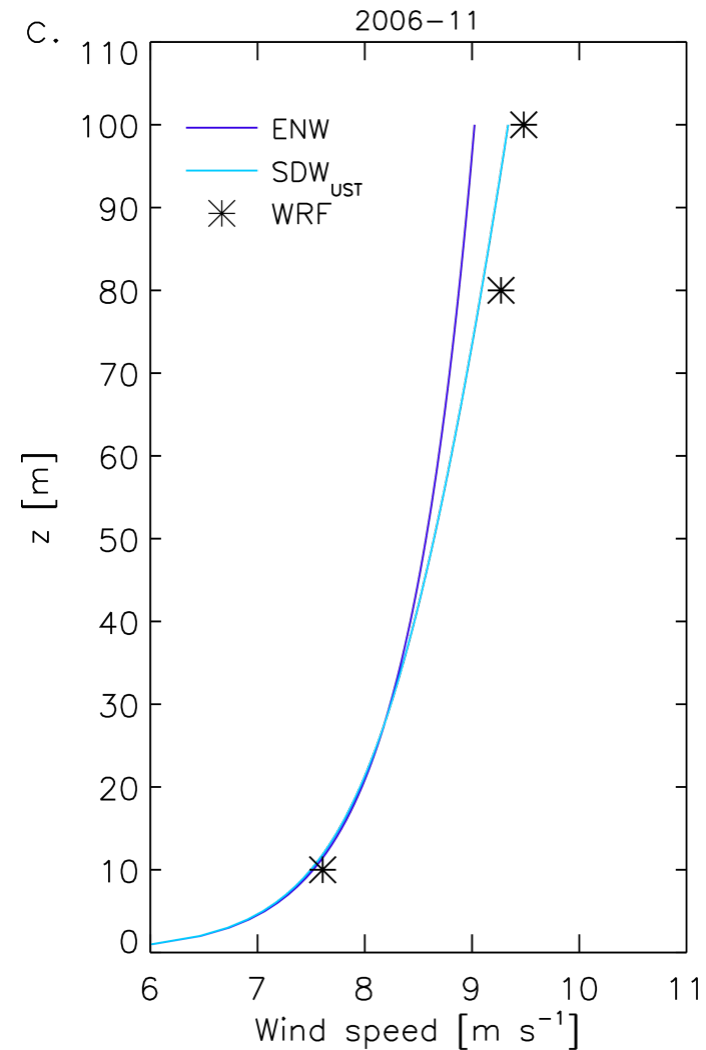


*10-m mean wind speed from  
KAMM mesoscale modeling*



# Long-term average wind profile

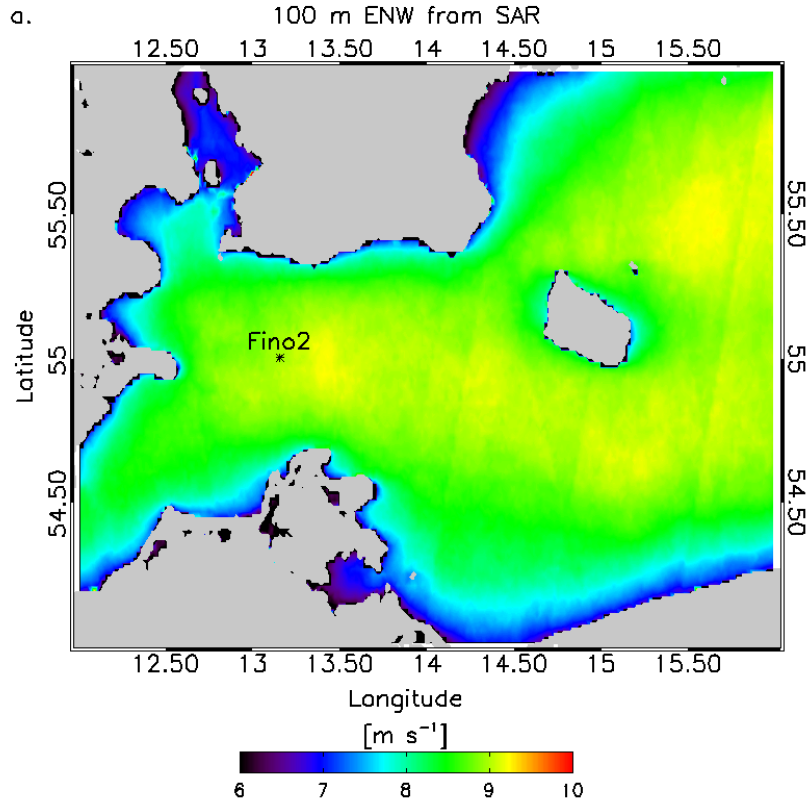
$$\left\langle \frac{\kappa u(z)}{u_*} \right\rangle = \ln \left( \frac{z}{z_0} \right) - \langle \psi_m \rangle$$



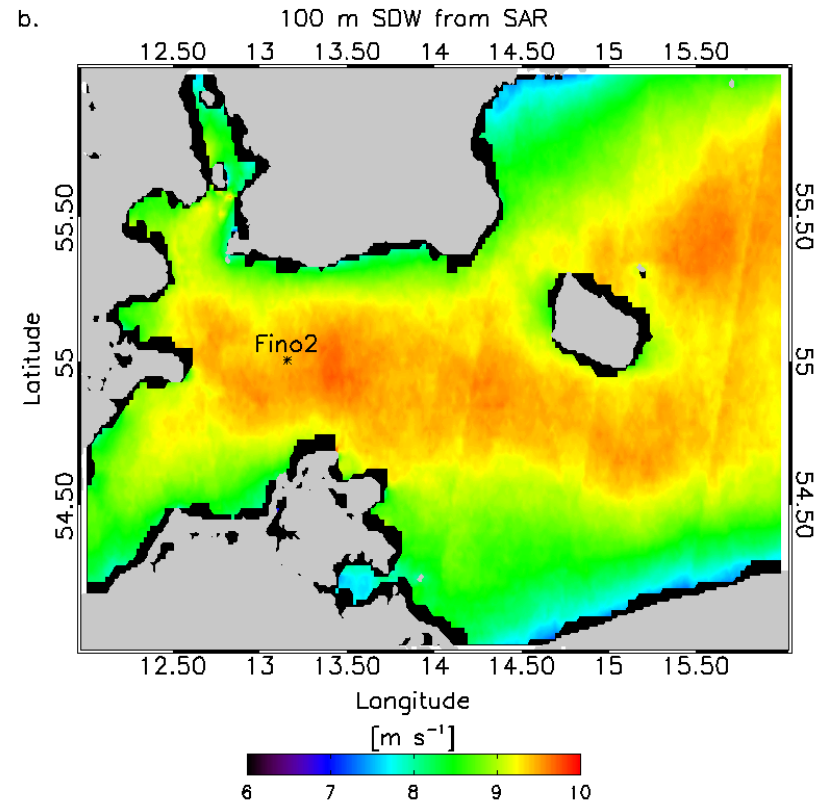
*Fino-2 in the South Baltic Sea*



# Wind speed extrapolated to 100 m



*Without stability correction*



*With stability correction*

Badger, M. et al.(2016): Extrapolating satellite winds to turbine operating heights, *Journal of Applied Meteorology and Climatology*, 44, 975-991, doi: 10.1175/JAMC-D-15-0197.1.

# Conclusions

- Future wind energy developments are global and high-wind issues must be considered
- SAR wind retrievals offshore are valuable for:
  - 1) Model validation
  - 2) Wind resource mapping
  - 3) Wind farm wake analyses
- Strength of SAR winds: a high spatial resolution
- Limitations of SAR winds: Lack of high-wind samples and information above the 10-m level above m.s.l.

# Acknowledgements

## Satellite data:

The European Space Agency (ESA)

## SAR wind retrieval systems:

JHU/APL and NOAA

## Mast observations:

All mast data accessed through the NORSEWInD project. Horns Rev: DONG energy and Vattenfall, Fino-1 and Fino-2: Deutsches Windenergie Institut, Egmond an Zee: NoordZeewind, Greater Gabbard: SSE Renewables.

## Funding:

EU-NORSEWInD, Icewind, New European Wind Atlas

## Collaboration:

Frank Monaldo & Christopher Jackson, NOAA